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MONTE CARLO MODELING OF LIGHT FIELD PARAMETERS IN OCEAN WITH PETZOLD LAWS OF SCATTERING*

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ABSTRACT

Results of Monte Carlo simulation of light fields in an absorbing and scattering ocean with all fifteen Petzold phase functions and 37 sun elevation angles between 0 and 90 degrees are presented. The computed values of diffuse reflectance for all 15 phase functions are regressed with the sun elevation. The simulations cover the range for phase functions eccentricity factor between 5 and 120 and the range of single-scattering albedo between 0.09 to 0.96. The results of the computation show the importance of the phase function and the sun elevation angle in determining diffuse reflectance. The approach shows how new computational abilities improve the probability of realistically modeling radiative transfer over a wide range of conditions.

1. INTRODUCTION

Broad availability of powerful desktop computers in recent years has made it possible to solve many radiative transfer problems in the sea by brute force, *i. e.*, to calculate a variety of scattering situations with different inherent optical properties (IOP) and sun elevations by Monte Carlo simulation and then try to derive regression equations for the apparent optical properties as a function of the inherent ones. Such a task is currently possible to accomplish even on a personal computer. This paper gives an example of such an approach. The regressions for diffuse reflectance coefficient of a realistic ocean illuminated by the sunlight are derived as a function of the sun elevation angle. The results show that for some cases the corrections to diffuse reflectance due to sun elevation angle can reach 40% and should always be taken into account in all procedures that attempt to retrieve the optical parameters of the sea from remotely measured data.

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2. MODELING

We modeled 555 cases with 10 million photon histories each for the 15 phase functions by Petzold (1972) with 37 sun elevations using a slightly modified code by Kirk (1981). The code was modified in such manner that it accepts as input an array of optical depths (401 values between 0 and 20), arrays of all Petzold phase functions, and arrays of absorption and scattering coefficients. The output consisted of arrays of directional downward and upward irradiances (E_d and E_u), upward and downward scalar irradiances (E_{0d} and E_{0u}), and radiances $L(\theta)$ at 72 angles θ at chosen optical depths τ. The downward, upward and total mean cosines ($\bar{\mu}_d$, $\bar{\mu}_u$ and $\bar{\mu}$), downward and upward diffuse attenuation coefficients (k_d and k_u), and diffuse reflectances $R(\tau, \mu_s)$, for all 37 sun elevations and for diffuse illumination by skylight were calculated by post processing the above mentioned Monte Carlo output. The results are so overwhelming that we present here only a small fraction of the computed information.

One of the interesting and important problems of optical oceanography and optical remote sensing is the angular dependence of ocean diffuse reflectance on the sun elevation angle. Previously this problem was addressed theoretically in papers by Haltrin (1985), Khalturin (1985), and Gordon (1989). Using results of Monte Carlo modeling, regressions for relative diffuse reflectance as a function of the sun elevation were derived.

In the paper by Haltrin (1985) it was shown that diffuse reflectance of the sea illuminated by the direct sun rays just under the sea surface can be represented as

$$R(\bar{\mu}, \mu_s) = (1-\bar{\mu})^2 \big/ \left[1 + \mu_s \bar{\mu}(4 - \bar{\mu}^2)\right] \tag{1}$$

where $\bar{\mu} = (E_d - E_d)/(E_{0d} - E_{0d})$ is the mean cosine, and μ_s is the cosine of the angle of the refracted sun rays in the sea:

$$\mu_s = \sqrt{1 - \cos^2 h_s / n^2}\,, \tag{2}$$

h_s is the sun elevation angle ($h_s = 90° - z_s$, where z_s is a solar zenith angle). Eqn. (1) shows that in the self-consistent approximation of Haltrin (1985) the reverse value of diffuse reflection linearly depends on the cosine of refracted sun rays. For that reason computed with Monte Carlo method relative diffuse reflectances are plotted against the cosine of refracted sun rays μ_s. The results of this plot are shown on Fig. 1. This figure also shows that only the case with the phase function # 1 is linearly dependent on μ_s. All other cases exhibit quadratic behavior represented by the following regression

$$r_\mu = R(90°)/R(\mu_s) = -c_0 + c_1\,\mu_s - c_2\,\mu_s^2. \tag{3}$$

the coefficients c_0, c_1 and c_2 in (3) are given in Table.1. The correlation between r_μ and μ_s is very strong: all r^2 except one (#9, r^2=0.9868) exceed 0.99.

The computed regressions (3) show strong dependence of the seawater diffuse reflectance on the sun elevation angle. The correction related to the sun elevation in some cases can reach 40% and cannot be ignored.

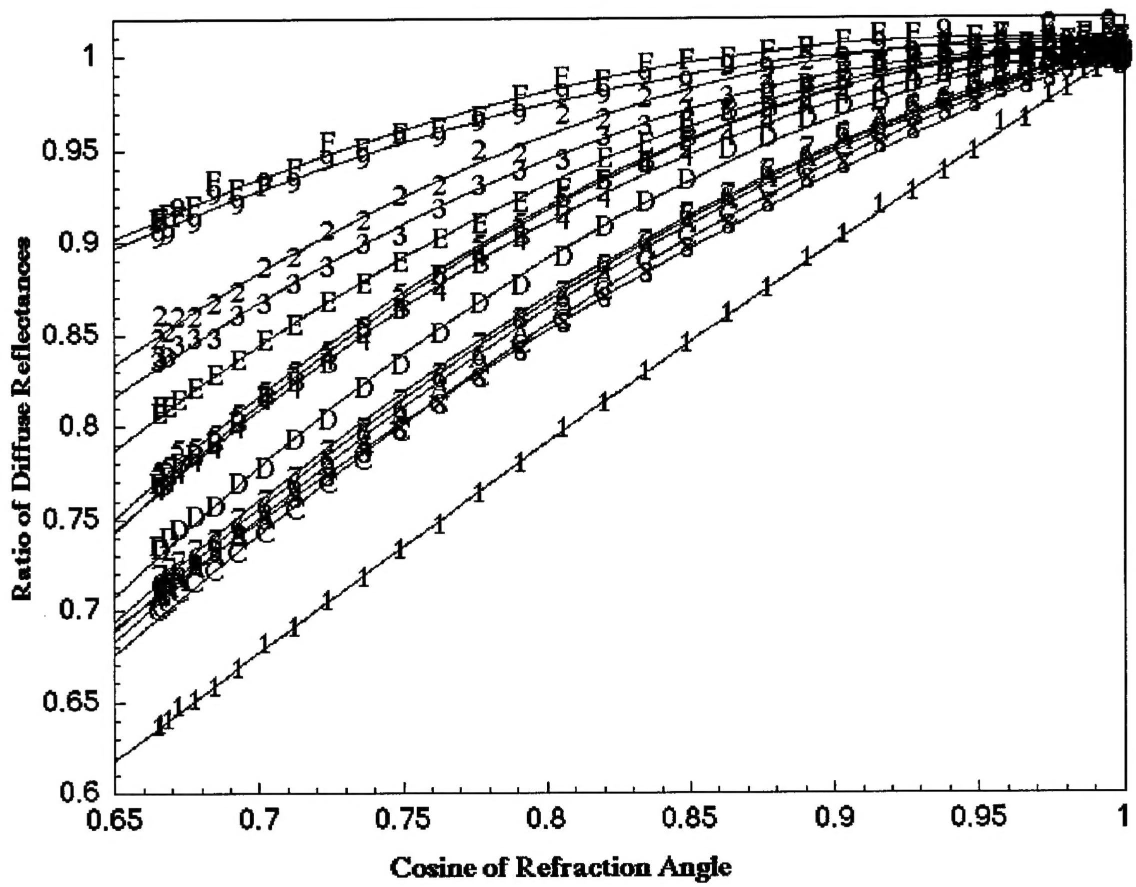

Fig. 1. Calculated by Monte Carlo simulation ratio of diffuse reflectances $r_\mu = R(90°)/R(\mu_s)$ as a function of the cosine of the refraction angle μ_s. Symbols are the Petzold phase function numbers in the hexadecimal system (*i.e.* A=10, B=11,.C=12, D=13, E=14, and F=15).

Table 1. Coefficients c_0, c_1, and c_2 for each of the fifteen Petzold phase functions with the corresponding values of inherent optical properties of water.

#	a, m^{-1}	b, m^{-1}	ω_0	B	b_B, m^{-1}	x	c_0	c_1	c_2	r^2
01	0.082	0.117	0.588	0.0250	0.002925	0.03444	0.2883920	1.587431	0.297748	0.9998
02	0.114	0.037	0.247	0.0440	0.001628	0.01408	0.5657793	3.233273	1.661429	0.9945
03	0.122	0.043	0.258	0.0380	0.001634	0.01322	0.5769344	3.189517	1.609438	0.9969
04	0.195	0.275	0.585	0.0140	0.003850	0.01936	0.9678525	3.865685	1.896918	0.9994
05	0.179	0.219	0.551	0.0130	0.002847	0.01566	1.024818	4.032690	2.003329	0.9985
06	0.337	1.583	0.824	0.0190	0.030077	0.08194	0.8523710	3.325892	1.469692	0.9990
07	0.366	1.824	0.833	0.0200	0.036480	0.09064	0.8102079	3.241494	1.426226	0.9993
08	0.125	1.205	0.906	0.0180	0.021690	0.14786	0.4779158	2.382291	0.900462	0.9995
09	0.093	0.009	0.093	0.1190	0.001071	0.01139	-0.024280	2.016210	1.035602	0.9868
10	0.138	0.547	0.798	0.0180	0.009846	0.06660	0.8470810	3.286625	1.435182	0.9992
11	0.764	0.576	0.430	0.0170	0.009792	0.01265	1.108715	4.216340	2.104504	0.9979
12	0.196	1.284	0.867	0.0150	0.019260	0.08947	0.7626112	3.037898	1.269881	0.9992
13	0.188	0.407	0.685	0.0170	0.006919	0.03550	1.057443	3.928398	1.866094	0.9988
14	0.193	0.081	0.463	0.0250	0.002025	0.02131	0.7187184	3.419936	1.696627	0.9985
15	0.085	0.008	0.091	0.1460	0.001168	0.01355	0.0408124	2.197559	1.149711	0.9900

An attempt to correlate these coefficients with the inherent optical properties given in Table 1 was made. Those relations are shown in Figures 2a.-2f. In spite of the strong regressional dependencies on inherent optical properties which exhibit all 15 Petzold phase functions (see Haltrin 1996), the coefficients in Table 1 fail to show any significant correlation with the IOP.

This negative result can be explained by errors of computation which are accumulated from two sources: 1) errors due to the discretization of the cumulative phase functions (CPF) which was used to compute angle of scattering, and 2) errors from the discretization of angles which accumulate the radiance distribution (both, the CPF and the radiance distribution were discretized with the 2.5° step; See Kirk, 1981). This problem should be addressed in future enhancements and development of Monte Carlo codes.

3. CONCLUSION

Some of the results of Monte-Carlo simulation of light fields in an absorbing and scattering ocean with all fifteen Petzold phase functions and 37 sun elevation angles between 0 and 90 degrees with 2.5 degree step were discussed. Downward and upward scalar and directional irradiances for 555 cases (15*37) were computed. All cases were computed for 401 different optical depths between 0 and 20 each with a 10 million number of photon histories.

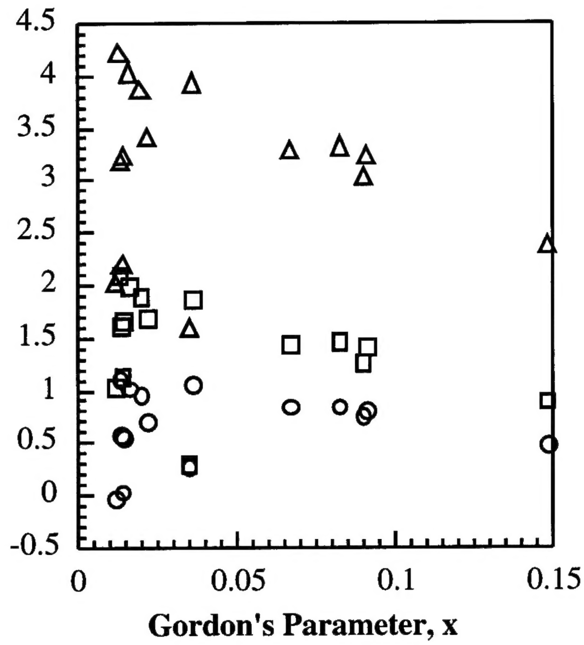

Fig. 2a. Regression coefficients $c_0(\text{O}), c_1(\Delta)$ and $c_2(\square)$ plotted against the Gordon's parameter $x = \omega_0 B/(1-\omega_0+\omega_0 B)$.

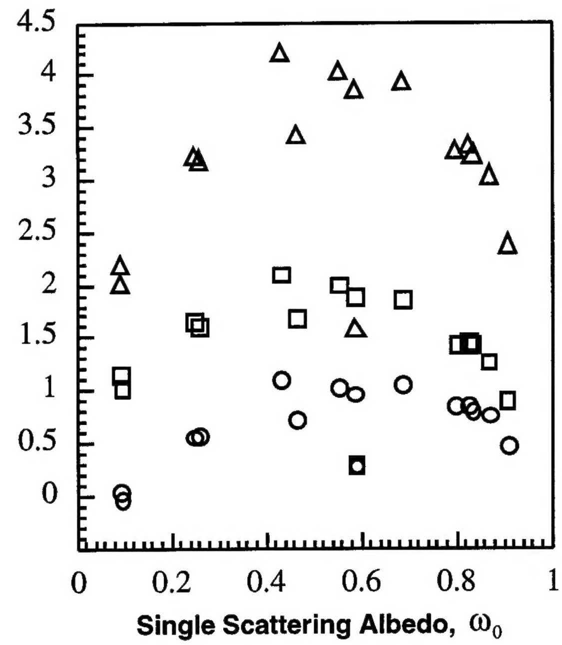

Fig. 2b. Regression coefficients $c_0(\text{O}), c_1(\Delta)$ and $c_2(\square)$ plotted against the single scattering albedo $\omega_0 = b/(a+b)$.

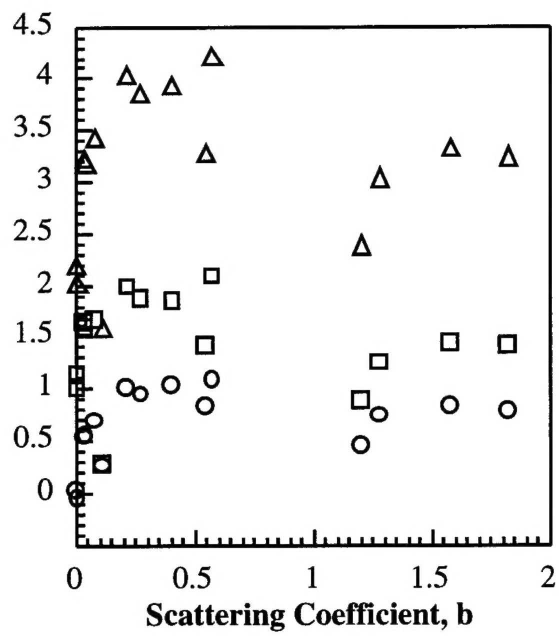

Fig. 2c. Regression coefficients $c_0(\text{O}), c_1(\Delta)$ and $c_2(\square)$ plotted against the scattering coefficient b.

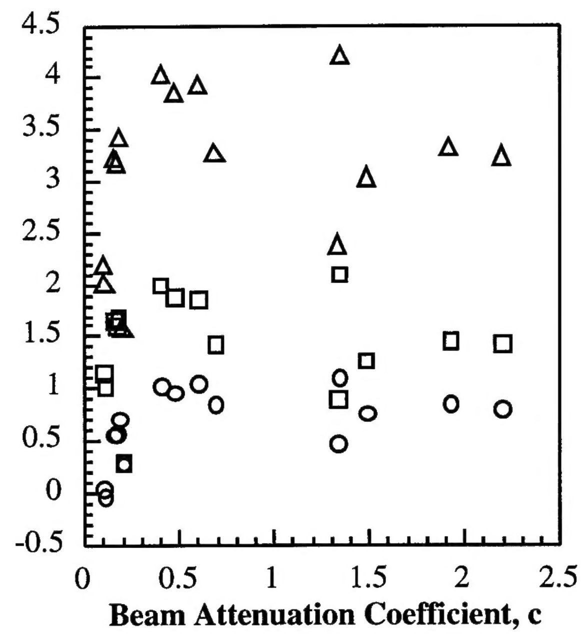

Fig. 2d. Regression coefficients $c_0(\text{O}), c_1(\Delta)$ and $c_2(\square)$ plotted against the beam attenuation coefficient $c = a + b$.

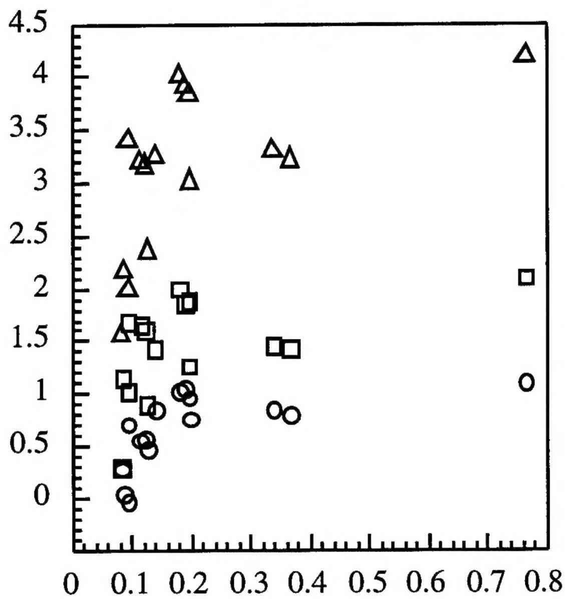

Fig. 2e. Regression coefficients $c_0(\mathrm{O}), c_1(\Delta)$ and $c_2(\square)$ plotted against the absorption coefficient *a*.

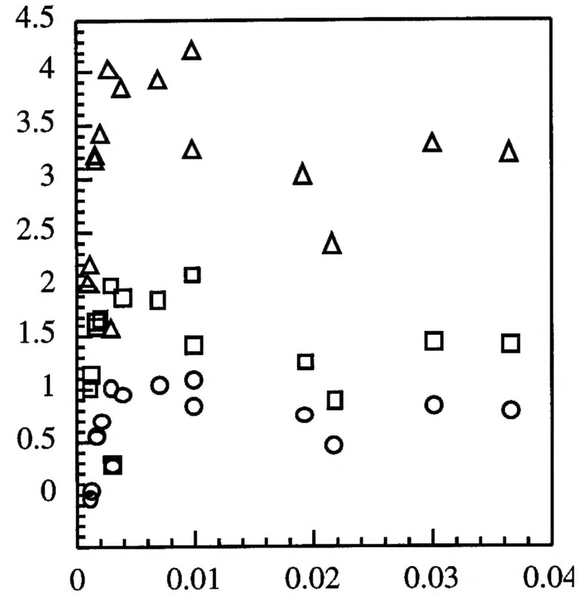

Fig. 2f. Regression coefficients $c_0(\mathrm{O}), c_1(\Delta)$ and $c_2(\square)$ plotted against the backscattering coefficient $b_B = bB$.

The computed values of the diffuse reflection were regressed against the cosine of sun refraction angle in seawater. The regression coefficients are very high (they exceed or equal to 0.99 for the whole range of parameters). The simulations cover the range of eccentricity factor for phase functions between 5 and 120 and the range of single-scattering albedo between 0.09 to 0.96. The computed regressions show strong dependence of the diffuse reflectance of seawater from the sun elevation angle. The correction related to the sun elevation in some cases can reach 40% and cannot be ignored.

The regressions are presented for the high and low single scattering albedo. The computed irradiances are compared overall to show the importance of the phase function in determining diffuse reflectance. The approach shows how new computational abilities improve the ability of realistically modeling radiative transfer over a wide range of conditions

4. ACKNOWLEDGMENTS

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